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Land use Changes and Northern Hemisphere Cooling

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Abstract

Recent reconstructions of Northern Hemisphere mean temperatures over the past millennium show a long-term cooling of about 0.25 K between 1000 and 1900 AD, prior to 20th century's warming. In this paper, we present the results of equilibrium climate model simulations that indicate that the land-use change occurring over this period may largely explain this observed cooling, although other factors also could have played a significant role. The simulated annual mean cooling due to land-use change is 0.25K globally and 0.37 K for the Northern Hemisphere, suggesting that the cooling of the prior centuries could have been largely the result of anthropogenic interference in the climate system.

Introduction

Recent reconstructions of Northern Hemisphere temperatures over the past millennium show a long-term cooling of about 0.25 K between 1000 and 1900 AD, prior to 20th century's warming (Mann et al., 1998; 1999). It has been suggested that this observed cooling is related to changes in astronomical forcing (Berger, 1988). An alternate hypothesis forwarded is that significant century-scale variability may be associated with solar irradiance variations (Lean et al., 1995). Here, we present the results of climate model simulations that indicate that the cooling due to land-use change occurring over this period is of the sign and magnitude to explain most of this observed cooling.

Previous studies on climate change and land use change have mostly looked at the effects of tropical deforestations and particularly the Amazonian deforestation (Shukla et al., 1990; Nobre et al., 1991; Dickinson et al., 1992; Dickinson and Kennedy, 1992; Sellers et al., 1993; Zeng et al., 1996; O'Brien, 1996; 1999). These studies show that changes in land use such as conversion of forest to grassland increase surface albedo and decrease surface roughness. The change in albedo decreases the net solar radiation absorbed at the surface and results in decreased surface temperature. The change in surface roughness decreases the evaporation and leads to increased surface temperature. Both changes result in decreased moisture convergence and reduced convective precipitation due to increased static stability (albedo effect) or due to reduced evaporation (roughness effect). These studies on tropical deforestation reveal that the change in surface roughness due to tropical deforestation increases the surface temperatures more than they were decreased by the change in albedo. Costa and Foley (2000) find that the effects of deforestation and increasing CO_2 on precipitation tend to counteract one another but both tends to warm the Amazon basin.

Boreal forest ecosystems may also affect climate (Bonan et al., 1992; Foley et al., 1994; Bonan, 1997; Hansen et al., 1999; Chase et al., 2000). The increase in albedo caused by deforestation of boreal of forest apparently overwhelms the warming effect due to reduced evaporation. Further, in mid and high latitudes, deforestation also exposes the underlying snow, reinforcing the cooling in a 'snow-albedo' feedback. Vegetation and soil feedbacks have been implicated in climate change (Foley et al., 1994; Kutzbach et al., 1996; Coe and Bonan, 1997) in the early Holocene.

Since most of the land use change took place in mid and high latitudes before the industrial era, it is possible that conversion of natural forests into cropland causes cooling and this can explain much of the observed Northern Hemisphere cooling in the last millennium. In this paper, we use an atmospheric general circulation model (AGCM) coupled to a slab ocean and thermodynamic sea ice model to investigate the climate change due to the replacement of natural vegetation into croplands that occurred prior to the industrial era. Indeed, we find that such a land use change causes a decrease in simulated Northern Hemisphere and global mean temperatures similar to that estimated from paleo-data reconstructions. We note that Chase et al. (2000) investigated the same issue of impacts of land-use change using the same AGCM and datasets, but their study was limited by the use of prescribed sea surface temperatures.

The Model

We adopt Version 3 of the Community Climate Model (CCM3) developed at the National Center for Atmospheric Research (Kiehl et al., 1998). This is a spectral model with 42 surface spherical harmonics to represent the horizontal structure of prognostic variables: the horizontal resolution is approximately 2.8° in latitude and 2.8° in longitude. The model has 18 levels in the vertical. An important aspect of CCM3 is that it has very little systematic bias in the top-of-atmosphere and surface energy budgets. Its climatology is in reasonable agreement with observations (Kiehl et al.,1998). We adopted a version of the model with a simple slab ocean-thermodynamic sea ice model, which allows for a simple interactive surface for the ocean and sea ice components of the climate system. The slab ocean model employs a spatially and temporally prescribed ocean heat transport and spatially prescribed mixed layer-depth, which ensures replication of realistic sea surface temperatures and ice distributions for the present climate.

Experiments

We performed two equilibrium climate simulations. One of these simulations, "1000AD", uses potential natural vegetation (Chase et al., 1996; 2000) and the other simulation, "1900AD", uses the standard CCM current vegetation dataset (Olson et al., 1983; Bonan, 1996). All other aspects of the two model simulations were identical. For CO_2 and other trace gases such as CH_4, N_2O, CFC-11 and CFC-12, the concentrations are specified at pre-industrial levels in both simulations. For both simulations, the model is run for 25 years from an initial state corresponding to pre-industrial climate and the climate statistics presented below are the averaged values over the last 15 years of model simulations.

The natural potential vegetation cover is created by taking the standard CCM dataset and filling in agricultural areas with appropriate natural vegetation types in keeping with standard CCM3 vegetation classifications (Chase et al., 2000). The natural potential vegetation type is estimated from the relationship between potential Leaf Area Index (LAI) and vegetation types (Neilson and Marks, 1994). Potential LAI is estimated using long-term precipitation, temperature, and soil data and empirical relationship between transpiration and LAI (Nemani and Running, 1989). The use of standard CCM3 vegetation types that correspond most closely to the estimated vegetation types (Nemani and Running, 1989) may contribute some inaccuracy but is unlikely to affect our basic results. Differences in vegetation categories between the two simulations resulted in changes in the fraction of the grid cell covered by vegetation, and vegetation physical and physiological properties.

Changes in exposed LAI and net solar radiation at the top of the atmosphere in regions of land use change are shown in Fig. 1. The affected regions are mostly in Europe, North America, India and Southeast Asia. Savanna, various types of forests, grassland and shrubland were replaced by various types of croplands (cool forest crop, warm forest crop, cool irrigated crop, cool crop, warm irrigated crop, warm crop). Such a conversion generally leads to a reduction in mean net solar radiation at the surface and top of the atmosphere. Our radiative forcing estimations yielded a mean shortwave radiative forcing of -0.28 W m^{-2} over land area due to these changes in land use.

Results

In Table 1, we have listed the annual means of global, Northern Hemisphere, and land surface mean surface temperature, precipitable water vapor. Table 1 also shows the annual means of global and Northern Hemisphere sea ice volume. The simulated annual mean cooling due to land-use change is 0.25K globally, 0.37 K for the Northern Hemisphere and 0.41 over land. We notice a corresponding decrease in precipitable water and increase in sea ice volumes in the current vegetation case. Our results are in qualitative agreement with a recent study (Hansen et al., 1999) where a simulated global mean cooling of 0.14 is obtained.

The model predicts that eastern and central North America, Middle East, and Southeast Asia cool more than the Northern Hemisphere average (Fig. 2a). The centers of cooling are located in these regions and extend to Greenland, Europe, Northern Africa and India. The cooling in these regions is statistically significant at the 5% level (Fig. 2b). In contrast, areas with warming and all temperature anomalies in the high latitudes are generally not statistically significant at this level.

In order to understand this simulated cooling, we show in Table 2, the annual means of global, Northern and Southern Hemisphere and land surface means of net surface solar radiation, precipitation and surface evaporation. We notice a decrease in net solar radiation in the global and Northern Hemisphere mean in the current vegetation case. This decrease is qualitatively in agreement with a recent modeling study (Hansen et al., 1999). Over land, a decrease of 1.86 W m^{-2} in the net absorbed solar radiation at the surface is simulated. Therefore, we conclude that the simulated cooling occurs primarily as a result of the higher albedo of agroecosystems as compared with the natural ecosystems they replaced.

In tropical deforestation studies (Shukla et al., 1990; Nobre et al., 1991; Dickinson et al., 1992; Dickinson and Kennedy, 1992; Sellers et al., 1993), it was found that the conversion of tropical forests into croplands significantly affected mean precipitation and evaporation. These changes were primarily due to local changes in tropical convection. In contrast to these studies, we find little changes in mean precipitation and evaporation (Table 2). This is because, in our study, the deforestation occurred mostly in mid latitudes where precipitation dynamics is less affected by local convection and is instead dominated by large-scale condensation associated with baroclinically driven storm tracks. Therefore, we conclude that little change in global scale hydrologic cycle is associated with historical land-use changes.

Discussion

We have performed "equilibrium" climate simulations using a single atmospheric general circulation model coupled to a slab-ocean and thermodynamic sea-ice model

(Kiehl et al., 1998). It is unlikely that the transition between "natural" and "modern" vegetation was smooth (Ramankutty and Foley, 1998; 1999). It is possible that other GCMs would yield quantitatively different results (Hansen et al., 1999), because the results may be highly sensitive to the formulation of the model and the parameterization of various physical processes. Climate models exhibit a wide range of response for similar climate forcings (Hansen et al., 1997). Simulations using a coupled atmosphere, dynamic sea ice and ocean general circulation model would include dynamical feedbacks that could amplify the regional or global climate change. Nonetheless, our results indicate that deforestation can cause significant climate perturbations and further efforts should be made to improve our understanding of the processes involved.

Our results indicate that land use change could explain most of the cooling inferred for the period from 1000 to 1900 AD (Mann et al., 1998; 1999). However, other factors could have also contributed to this cooling, including internal oscillations related to ocean-atmosphere coupling, changes in earth's orbital parameters (Berger, 1988), or century-scale climate variability associated with solar irradiance variations (Lean et al., 1995). We have verified that our "model" is relatively insensitive to changes in earth's orbital parameters. The change in global and annual mean surface temperature is of the order of 0.01 K for orbital parameters corresponding to glacial (114,000 BP) and interglacial (125,000 BP) periods. The maximum range of changes in solar irradiance is ~ 4 w m^{-2} from 1600 AD to present (Lean and Rind, 1998). Taking into consideration Earth's albedo and geometry, this corresponds to a climate forcing of 0.7 w m^{-2}, and a temperature increase of 0.32 K, since the climate sensitivity of our model is 0.45 K/w^{-2} (Govindasamy and Caldeira, 2000). This is indeed similar in magnitude but opposite in sign to the temperature change we find due to land use change. Because solar luminosity is inferred to have increased since 1600 AD, solar variability may be an important factor affecting climate over the past millenium, but is unlikely to explain the cooling between in the period prior to 1900 AD.

Nevertheless, we wish to emphasis that the goal of this paper not to explain all of the factors that could have contributed to the inferred Northern Hemisphere cooling since 1000 AD, or to systematically investigate all the possible causes of this cooling. Rather, our goal is to assess the climatic impact of land use changes and understand whether this could have been an important factor contributing to Northern Hemisphere cooling. Since the model simulated temperature change is similar in sign and magnitude to the observed temperature change since 1000 AD, we suggest that land use change is a potentially important factor contributing to this cooling. Of course, other factors may also prove to be important. The observed datasets are too sparse at present to test the land-use-change/global-cooling hypothesis with detailed spatial resolution; however, this prediction is in principle testable. We urge the collection of additional paleoclimate datesets that can be used to test the hypothesis that land-use changes contributed to the observed Northern Hemisphere cooling between 1000 and 1900 AD.

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Table 1. Climate Statistics: Annual means of global, Northern Hemisphere and Land means of surface temperature, precipitable water and sea ice volume in "1000AD" and "1900AD" simulations and the difference between them.

Case	Surface Temperature (K)			Precipitable water (mm)			Sea ice Volume (x 10^{12} m^3)	
	Global	NH	Land	Global	NH	Land	Global	NH
1000AD	285.75	286.20	278.43	25.32	26.05	19.52	50.65	77.08
1900AD	285.50	285.83	278.02	24.87	25.16	19.21	51.20	78.86
Change	-0.25	-0.37	-0.41	-0.45	-0.89	-0.31	0.55	1.78

Table 2. Climate Statistics: Annual means of global, Northern and Southern Hemisphere and Land means net surface solar radiation, precipitation, and evaporation in the "1000AD" and "1900AD" simulations and the difference between them.

Case	Net surface solar radiation (W m^{-2})			Precipitation (mm day^{-1})			Evaporation (mm day^{-1})		
	1000AD	1900AD	Change	1000AD	1900AD	Change	1000AD	1900AD	Change
Global	172.24	171.77	-0.47	2.98	2.98	0.0	2.98	2.98	0.0
NH	170.56	170.13	-0.43	3.03	2.93	-0.1	2.87	2.87	0.0
SH	173.92	173.41	-0.51	2.93	3.03	0.1	3.09	3.09	0.0
Land	145.77	143.91	-1.86	2.16	2.21	0.05	1.47	1.50	0.03

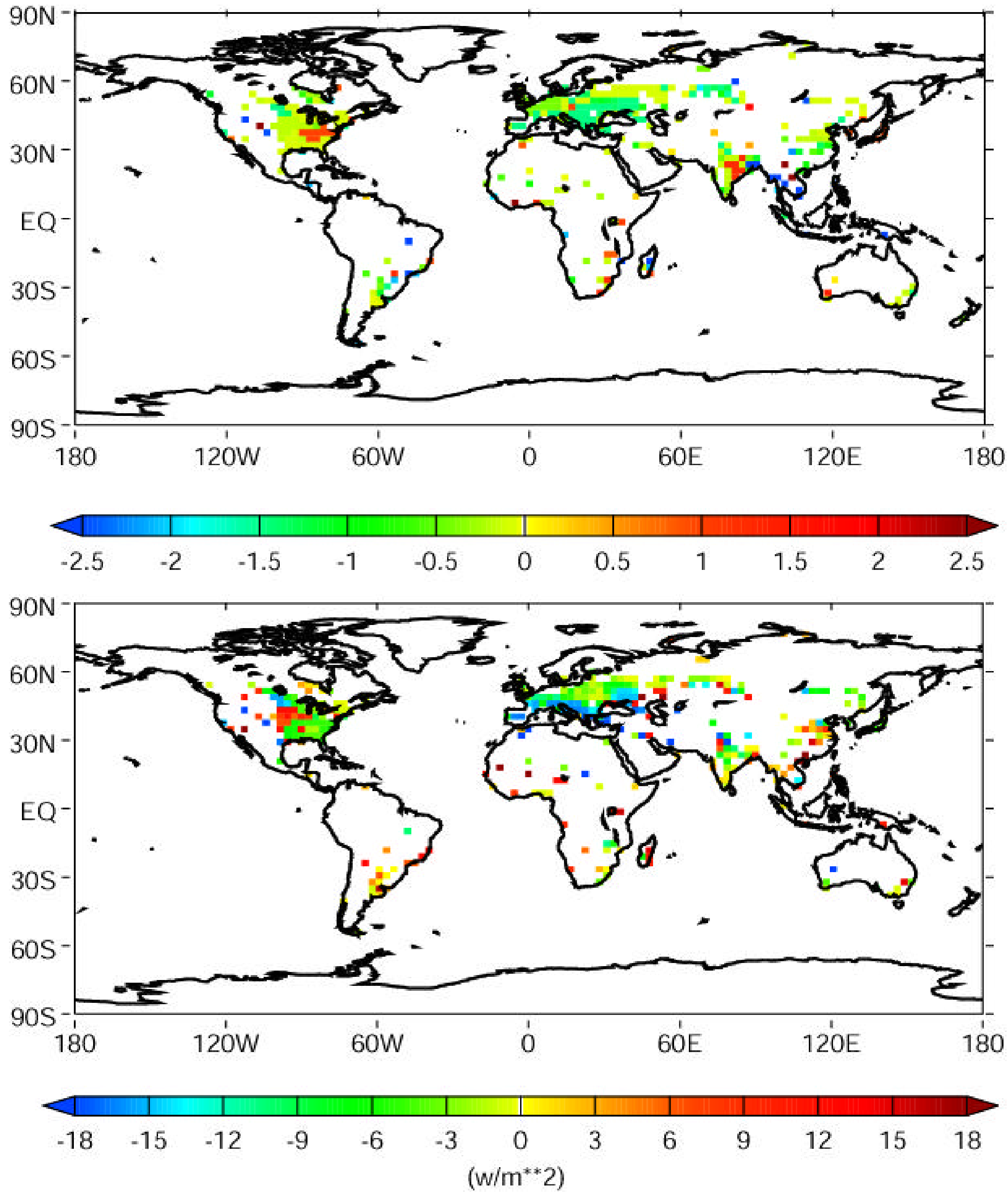

Fig. 1. Change in annual mean exposed Leaf Area Index (top panel) and net solar radiation at the top of the atmosphere (bottom panel) due to the conversion of natural potential vegetation into croplands by anthropogenic interference prior to the industrial era.

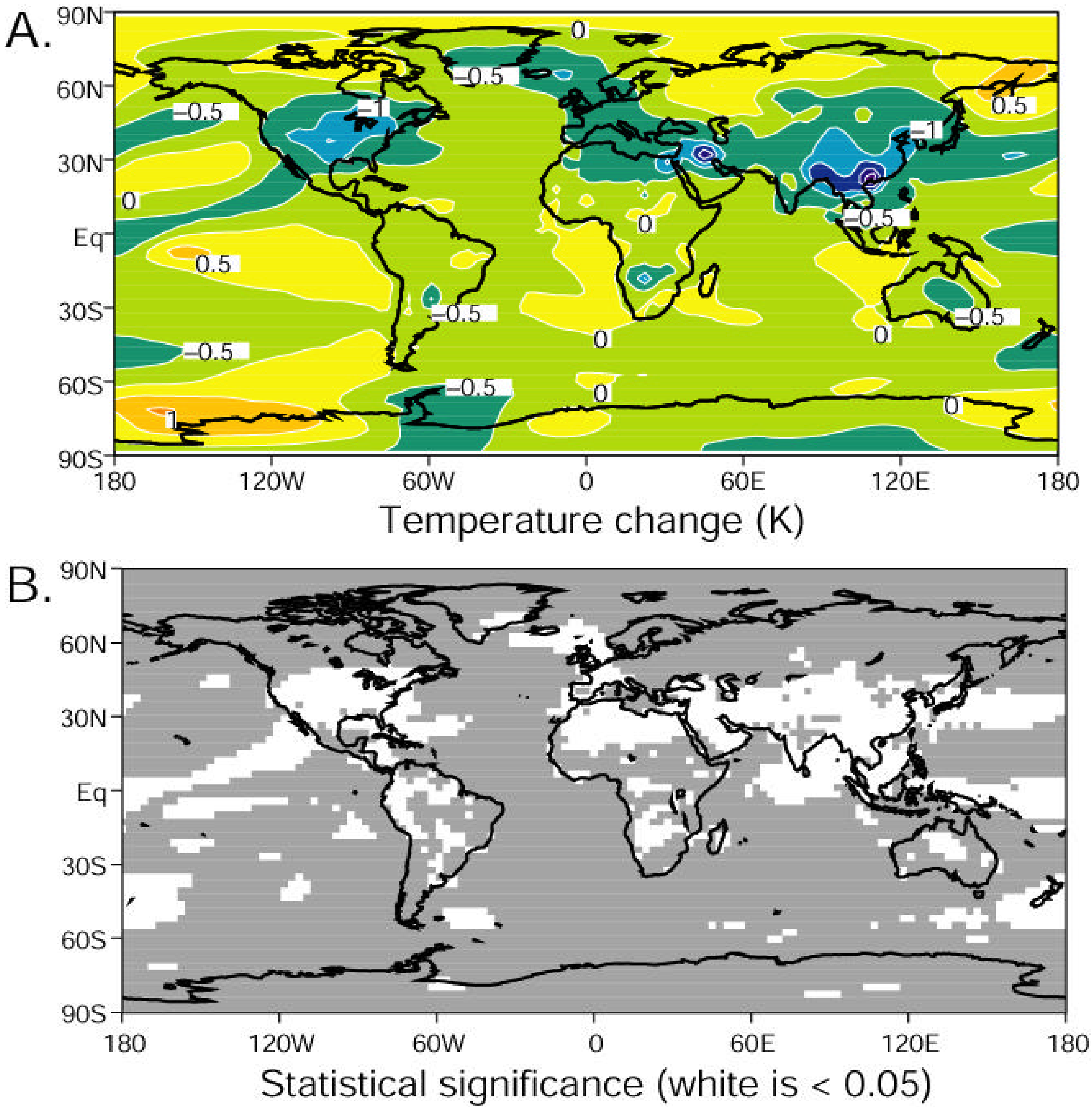

Fig. 2 a) Simulated surface temperature change due to conversion of natural vegetation to croplands. Simulated surface temperature cools most significantly over central and eastern North America, Middle East, and Southeast Asia. The contour interval is 0.5 K. b) The regions where the cooling is significant at the 5 % level.